Temporal Variations of the Anomalous Oxygen Component

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We have used data from the cosmic ray experiment (CRS) on Voyagers 1 and 2 to examine anomalous oxygen in the time period from launch in 1977 to the end of 1981. We find several time periods where large periodic (typically 26 day) temporal variations of the oxygen intensity between ~5 - 15 MeV/nuc are present. Variations in intensity by up to a factor of 10 are observed during these periods. We find that several characteristics of these variations indicate that they are not higher energy extensions of the low energy particle (~1 MeV/nuc) increases found in many corotating interaction regions (CIR's). Many of these periodic temporal variations are correlated with similar, but much smaller, recurrent variations in the >75 MeV proton rate. We have compared Voyager 1 and Voyager 2 counting rates to estimate the local radial gradient for both the protons and the oxygen. The proton gradients during periods of both maximum and minimum fluxes are consistent with the overall positive radial gradients reported by others from Pioneer and near-Earth observations, supporting the view that these variations are due to local modulation of a source outside the radial range of our measurements. In contrast, the oxygen gradients during periods of maximum proton flux differ in sign from those during minimum proton fluxes, suggesting that the origin of the oxygen variations is different from that of the protons.

INTRODUCTION

The anomalous component of cosmic rays has now been studied for about a decade. As described in the accompanying paper the anomalous particle populations exhibit long term variations due to solar modulation effects. Indeed, almost all of the existing studies of anomalous oxygen have been made using rather long time averages, typically on the order of months. The four CRS telescopes on each of the two Voyager spacecraft, with their large collecting power, have allowed us to look at the anomalous oxygen rates with finer time resolution for the first time. We have examined the period from launch in late 1977 to the end of 1981 and we find several time periods where large recurrent temporal variations are present, with an ~26 day periodicity. Variations in intensity by a factor of up to 10 are observed. We have investigated the origin of these variations by comparing the oxygen rates to rates of other particle types and by intercomparing the rates of the two Voyagers.

OBSERVATIONS

An example of the oxygen counting rate variations during 1980 is shown in the lower panel of Figure 1. The high energy proton rate is plotted in the upper panel and four major correlated peaks in the two rates are indicated by the dashed lines. The amplitude of the proton variations is ~10 - 15% , whereas the variation in the oxygen rate is much larger with a peak to valley ratio of perhaps 10 to 1 for the largest peaks. The average spacing between the four large proton peaks in the figure is ~26 days.

The first report of ~26 day intensity variations in anomalous oxygen was by *Webber et al.* [1979] based on a subset of this data for the period just after launch in 1977. In that observation variations in amplitude by a factor of two were found. *Von Rosenvinge and Paizis* [1981] reported 27-day variations of a factor of two in anomalous oxygen using near-Earth data during 1976. We also note that 27-day intensity variations of up to a factor of two for the anomalous helium component have been previously re-

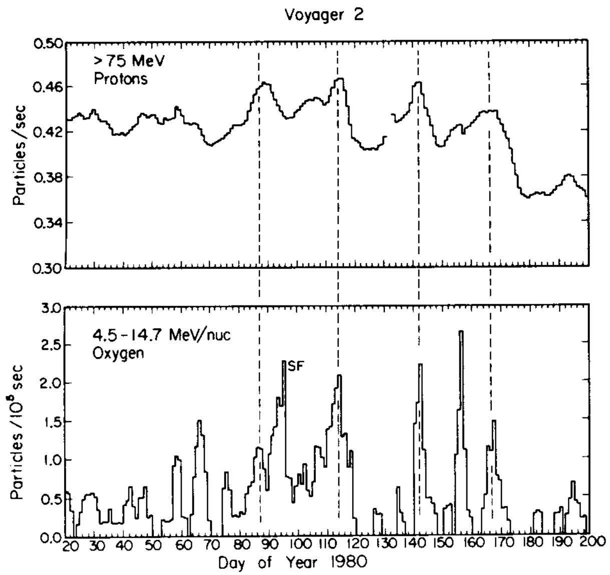

Fig. 1. Voyager 2 3-day moving average counting rates versus time of high energy protons and anomalous oxygen in 1980. The dashed lines relate the largest peaks in the proton rate to peaks in the oxygen rate. The peak labeled SF is probably due to a solar flare.

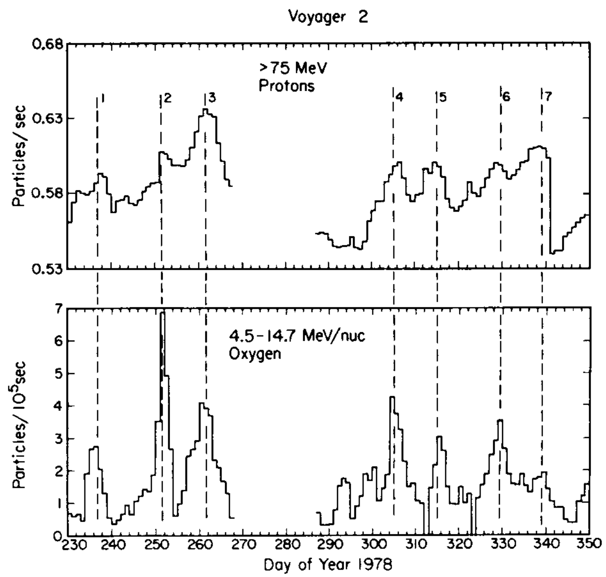

Fig. 2. Voyager 2 3-day moving average counting rates versus time of high energy protons and anomalous oxygen in 1978. The seven dashed lines mark correlated peaks in the two rates. The data from day 269 to day 286 have been removed because of a large solar flare.

ported by several groups [*Garcia-Munoz et. al*, 1977; *Bastian et. al*, 1979; *Von Rosenvinge and Paizis*, 1981]. Our analysis of the anomalous helium data is only preliminary but we are finding that the amplitude of the helium intensity variations are a factor of two or less throughout the period while the oxygen variations are much larger.

In Figure 2 the oxygen and proton counting rates are shown for a 120 day period in 1978. Here again, oxygen intensity variations of up to a factor of 10 are observed. Seven correlated increases are marked by the dashed lines. The odd numbered lines are on ~26 day increments. The even numbered lines are also essentially on 26 day increments and occur ~10 days in advance of an odd numbered line. This timing is suggestive of increases associated with CIR's and indeed this period has been studied for CIR increases at lower energies, ~1 MeV/nuc, by other Voyager investigators [*Hamilton et al.*, 1979].

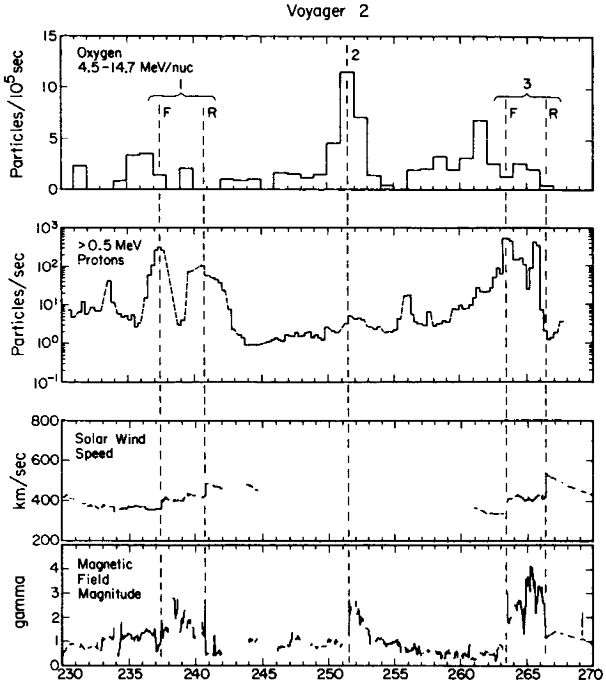

Fig. 3. Four plots from Voyager 2: (upper panel) daily averaged counting rate versus time for anomalous oxygen; (second panel) 6-hour averaged counting rate versus time for low energy protons; (third panel) hourly averaged solar wind speed from the MIT plasma experiment; (lower panel) hourly averaged magnetic field magnitude from the GSFC magnetometer experiment. Two CIR's are indicated by the dashed line pairs labeled 1 and 3, respectively. The forward and reverse shocks are labeled F and R, respectively. The number labels associated with the dashed lines correspond to those on Figure 2.

COMPARISON WITH CIR-TYPE INCREASES

We have investigated the possibility that the oxygen variations are the result of CIR acceleration. Plots of the rate of oxygen, the rate of > 0.5 MeV protons, which are a sensitive indicator of CIR acceleration, and plots of the solar wind speed and magnetic field magnitude are shown in Figure 3 for the period 1978, days 230-270. Two CIR's are indicated by the dashed line pairs labeled 1 and 3 which mark associated forward/reverse shock pairs. *Hamilton et al.* [1979] found that at ~1 MeV/nuc most of the enhanced carbon and oxygen intensity was concentrated near the reverse shocks and that the C/O ratio at this time was ~0.68. We find, on the other hand, that most of the higher energy oxygen precedes the forward shock. In addition, the oxygen increase near day 251, labeled with the dashed line number 2, is not associated with an identified CIR. Furthermore, we find very little carbon in our energy interval. For the sum of the seven peaks in the 1978 120 day period shown in Figure 2 the C/O ratio is less than 0.05. Finally, the energy spectrum of the increases is not what one would expect from a normal CIR event. The oxygen energy spectra in and between the seven 1978 peaks on Voyager 2 are shown in Figure 4. The shape of the two spectra are similar with both having a plateau near 6 MeV/nuc. The dashed line represents an upper limit to the spectrum of oxygen from a CIR estimated by scaling from our measured CIR helium spectrum on day 265, one of the largest such increases during this period. Indeed, this estimated oxygen CIR spectrum is derived for a reverse shock whereas most of our oxygen particles are at or near the forward shocks. By directly comparing the measured rates of helium and oxygen at comparable energies and by assuming a CIR He to O ratio of 150 to 1, we estimate that at the forward shocks the contribution from CIR-type acceleration to the anomalous oxygen increases is at the 1% level.

COMPARISON WITH HIGH-ENERGY PROTONS AND DETERMINATION OF RADIAL GRADIENTS

Another possibility for the origin of the oxygen variations is that they result from the same process responsible for the variations in the high energy proton rate, examples of which were shown in Figures 1 and 2. The proton variations are probably indicative of short term solar modulation effects. While the percentage variation of the oxygen rate is much larger than that of the proton rate, typically 50 times as large, it is possible that short term modulation effects may be playing a significant role for the oxygen as well. We have investigated this possibility from several viewpoints, including comparing the long and short term correlations of the oxygen and proton rates and comparing the radial gradients of the two particle populations. Here we shall consider the radial gradient data and some of its implications. The large scale radial gradients for the anomalous oxygen and the > 75 MeV protons have been previously reported by others for the 1 - 20 AU range by comparing the intensities at the Pioneer spacecraft to those near Earth. By using the separation of the two Voyager spacecraft we can determine the local radial gradients during the time intervals of the variations and compare these to the large scale gradients.

The relative positions of the two spacecraft projected into the solar equatorial plane are shown in Figure 5. The 1978 and 1980 periods we have studied are indicated by bars along the trajectory. In the 1978 period the spacecraft are ~4 AU from the Sun and ~0.3 AU apart. In 1980 they have moved out to an average radial position of ~7.2 AU and have moved apart ~ 1.25 AU. They are well aligned in both longitude (see Figure 5) and latitude (within 1 degree in 1978 and within ~0.3 degree in 1980). Note that during the 1978 and 1980 time intervals Voyager 1 is always farther from the Sun than Voyager 2. Thus for positive radial gradients Voyager 1 will measure a higher intensity than Voyager 2.

The comparison of the Voyager 1 and 2 proton rates for the 1978 period is shown in Figure 6. The correlation of features in the two plots is generally good. We have taken the ratio of the Voyager 1 to Voyager 2 intensities for the correlated maxima and minima of the vari-

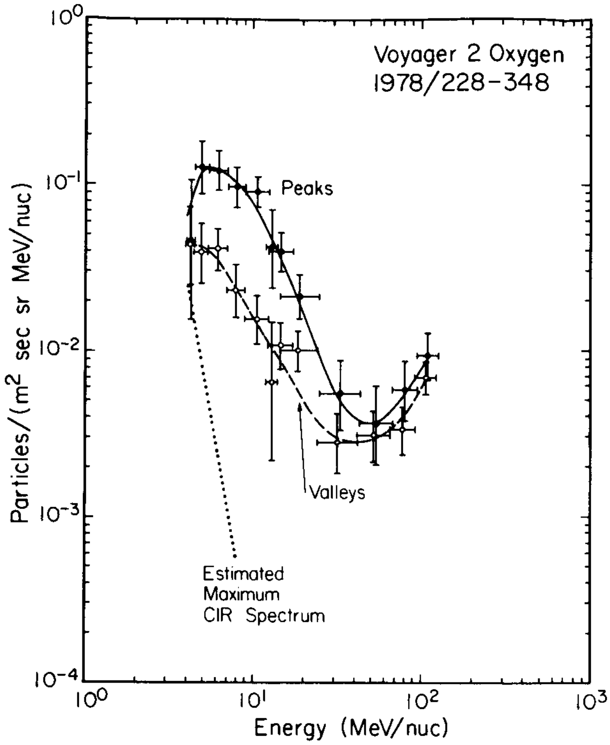

Fig. 4. Energy spectra of oxygen for selected time intervals in the period 1978 days 228-348. The upper points are for intervals in the peaks of the time variations. The lower points are for intervals between the peaks. The dotted line represents an estimated maximum CIR spectrum of oxygen.

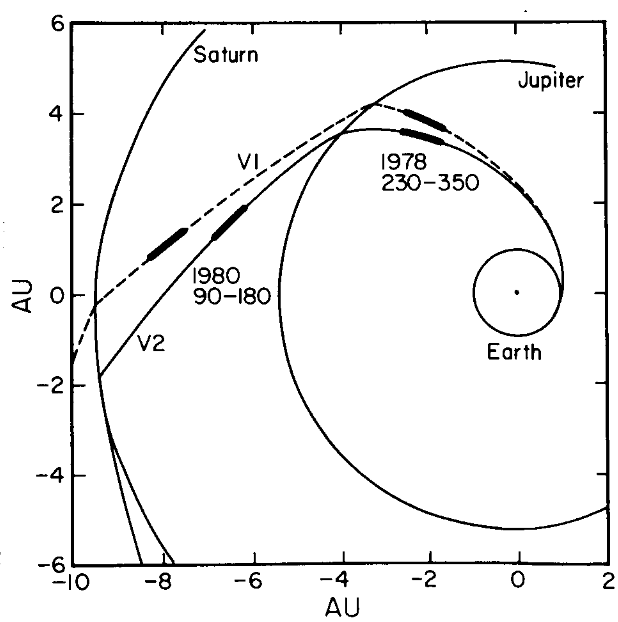

Fig. 5. Trajectory plot of the two Voyager spacecraft. The heavy bars mark the trajectory during the 1978 and 1980 periods of study.

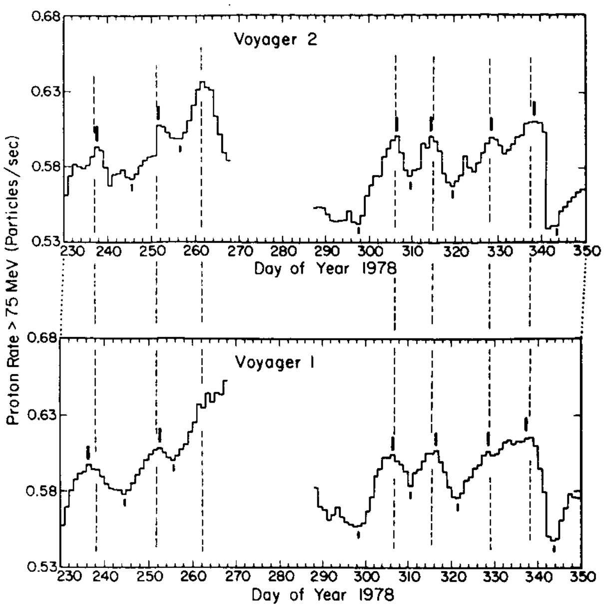

Fig. 6. Three-day moving average counting rate versus time of Voyager 1 and 2 high energy protons in 1978. The two plots are shifted relative to each other by 1 day to approximately account for the corotation delay between the two spacecraft. The dashed lines mark corresponding peaks in the two plots. The long vertical bars mark the actual peak 3-day intervals chosen in calculating the Voyager 1 to Voyager 2 counting rate ratios. The short vertical bars mark the corresponding times between the peaks. The rates were normalized in December 1977 when the two spacecraft were the same distance from the Sun.

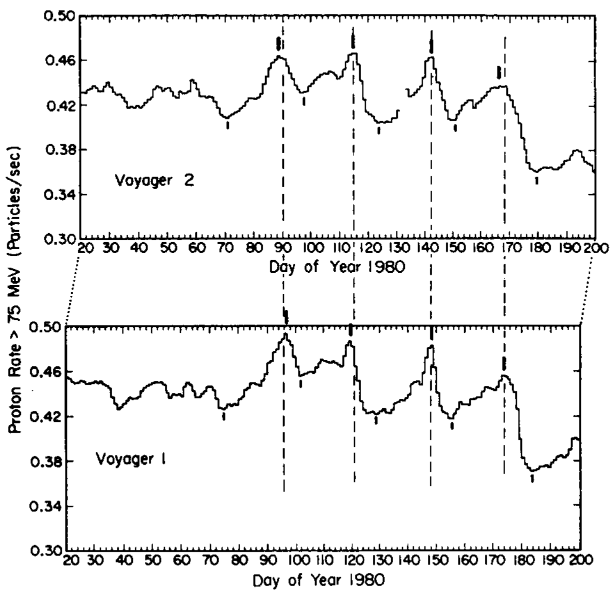

Fig. 7. Three-day moving average counting rate versus time for Voyager 1 and 2 high energy protons in 1980. The two plots are shifted relative to each other by 6 days to approximately account for the corotation delay between the two spacecraft. The dashed lines, vertical bars, and normalization are as described in the caption for Figure 6.

ations at the times indicated by the long and short vertical bars. The corresponding plot for the 1980 period is shown in Figure 7. The corotation delay is ~6 days for this time interval and, after making the time shift, the features in the two panels line up well. The intensity ratios corresponding to the data in Figures 6 and 7 are shown in Figure 8 as a function of average radial distance from the Sun as the points near 4 AU for 1978 and near 7.2 AU for 1980. The lower panel of Figure 8 shows the ratio for the peak times and the upper panel shows the ratios for the times between the peaks. The remaining points near 6.4 AU are for a 1979 period when variations were also observed. The dashed lines on both panels show the computed intensity ratio for a given local radial gradient. It is apparent that the data from both panels are consistent with a local radial gradient of ~3 - 5%/AU which is consistent with the large scale gradients found for these particles from the Pioneer and near-Earth observations [*McKibben et. al*, 1982]. This data therefore supports the notion that the variations in intensity of the protons are due to a local modulation effect, most likely produced by a corotating magnetic field structure.

The Voyager 1 and 2 anomalous oxygen rate comparisons for the 1978 period are shown in Figure 9. The dashed lines indicate times of maximum proton fluxes from Figure 6. We could not duplicate the analysis procedure we used for the protons because of poorer statistics. Therefore we have summed over the time intervals shown by the horizontal bars to get a single ratio for the periods between the maxima of the proton fluxes. We have also summed over the seven 3-day periods associated with the proton flux maxima in order to calculate a single average ratio for the "peak" times. These values are shown in the first column of Table 1. The V1 to V2 ratio for the times between the peaks is within 1σ of the expected ratio of 1.05 for the large scale positive radial gradient of ~15%/AU which has been reported for anomalous oxygen from Pioneer and near-Earth data [*Webber et al.*, 1981]. The ratio for the sum of the seven peaks is $\sim 1.8\sigma$ less than 1.05. For comparison the second column of Table 1 shows

the average V1 to V2 ratios for the high energy protons in 1978 as computed from the weighted average of the points shown in Figure 8. Ratios for both the peak and between-peak fluxes are consistent with the expected ratio for a radial gradient of 3 - 5%/AU.

In Figure 10 we show the anomalous oxygen rate comparisons for 1980. Here the situation is more difficult than in 1978. The correlation of features in the Voyager 1 and 2 plots is less clear. We have made a relative shift of 6 days in the two plots just as we did for the protons, and the times of the four major proton peaks are shown by dashed lines and used as a guide in identifying the correlated peaks. The 3-day periods indicated by the vertical bars were summed to get an average ratio for the peak periods. The times indicated by horizontal bars were summed to calculate a between-peak period ratio. This division of time periods is less obvious in 1980 than in 1978. For example, there appear to be additional peak fluxes in oxygen between the times associated with proton flux maxima, particularly near day 157 in Voyager 2 and near day 108 in Voyager 1. In fact there may well be a second sequence of peaks offset from the primary sequence by ~ 10 days. A 5-day data gap from day 130-135 on Voyager 2 possibly obscures one of the peaks in the secondary sequence. The V1 to V2 ratios of the anomalous oxygen intensity are shown for the two time periods in the third column of Table 1. Here again the ratio for the times between the proton peaks is within 1σ of the expected ratio of 1.2. However, the ratio for the sum of oxygen fluxes during periods associated with proton flux maxima is $\sim 3.7\sigma$ less than expected for a gradient of +15%/AU. The average proton intensity ratios, shown in the fourth column of Table 1, are again consistent with a 3 - 5%/AU radial gradient.

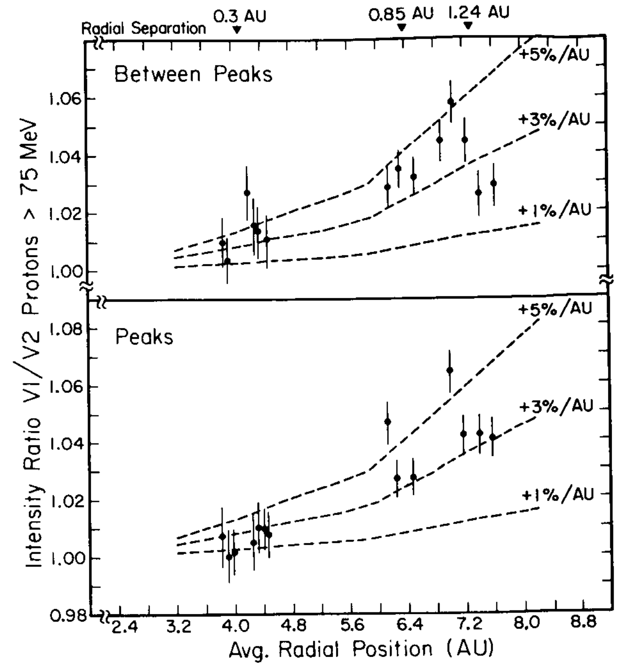

Fig. 8. Voyager 1 to Voyager 2 high energy proton counting rate ratio versus average radial distance from the Sun for selected 3-day periods. The points near 4 AU and 7.2 AU correspond to the indicated days shown in Figure 7 and 8, respectively. The three points near 6.4 AU correspond to similar periods in 1979. The dashed lines represent the expected ratio for a given local radial gradient. The approximate radial separations of the two spacecraft are indicated at the top of the upper panel.

DISCUSSION

As we have noted, the >75 MeV proton variations appear to be small (~ 10 - 15%) perturbations on a rate which is well correlated over the separation distance of the two spacecraft. The local gradient derived for both the maxima and minima of the variations are consistent with the large scale gradients reported for separation distances of up to 20 AU. The oxygen variations, on the other hand, do not fit a similar picture. Particularly in 1980 (see Figure 10) when the spacecraft are ~ 1.25 AU apart, the features in the two rates are not well correlated; the peaks in Voyager 2 appear to be sharper and more well defined than in Voyager 1, the perturbations on the rate are not small, and the apparent local radial gradients for the peaks do not agree with the overall large scale gradients that have been reported. The oxygen intensity variations appear to be more filamentary in nature than those of the protons, suggesting perhaps that the oxygen nuclei are more sensitive to the detailed configuration of the magnetic field than are the protons. These differences suggest that the origin of the short term oxygen variations is different from that of the protons. (See *Hovestadt et. al* [1979] for an indication of differences in the origin of long term variations of oxygen and protons.)

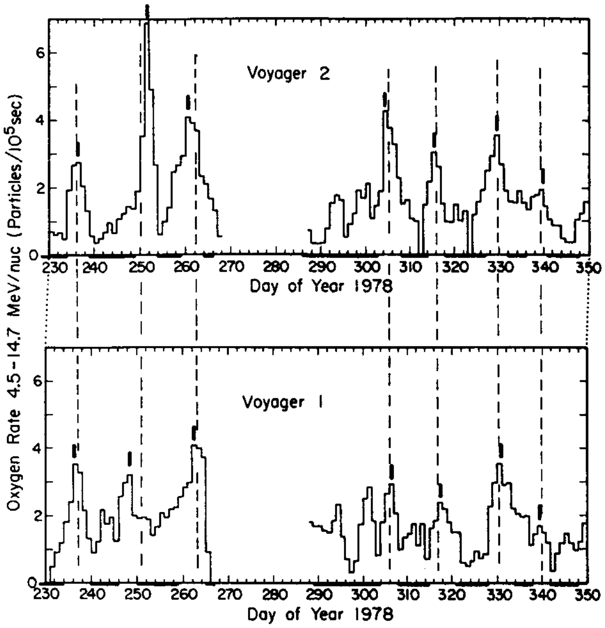

Fig. 9. Three-day moving average counting rate versus time for Voyager 1 and 2 anomalous oxygen in 1978. The two plots are shifted relative to each other by 1 day to approximately account for the corotation delay between the two spacecraft. The dashed lines mark the approximate position of correlated peaks in the Voyager 2 high energy proton rate. The heavy vertical bars mark the actual peak 3-day intervals chosen in calculating the Voyager 1 to Voyager 2 counting rate ratio. The horizontal bars mark the corresponding times chosen between the periods associated with proton flux maxima.

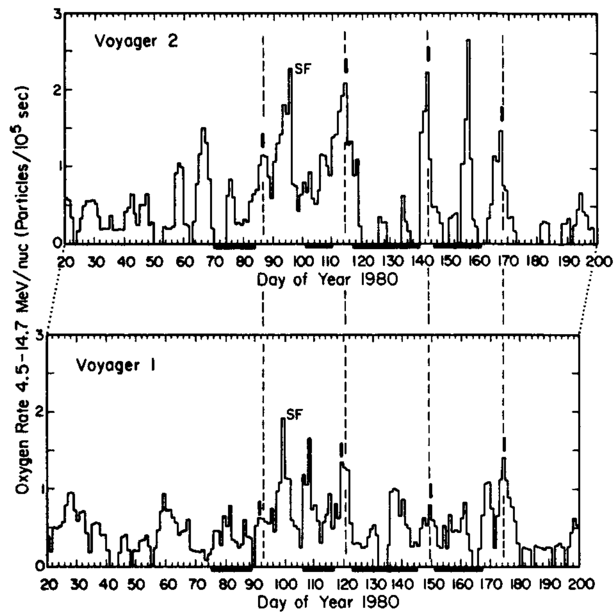

Fig. 10. Three-day moving average counting rate versus time for Voyager 1 and 2 anomalous oxygen in 1980. The two plots are shifted relative to each other by 6 days to approximately account for the corotation delay between the two spacecraft. The dashed lines mark the location of the largest peaks in the Voyager 2 high energy proton counting rate plot. The peak labeled SF in both panels is probably due to a solar flare. The vertical and horizontal bars are as described in the caption for Figure 9.

TABLE 1. Ratios of V1 to V2 Intensity

	1978		1980	
	Anomalous oxygen	>75 MeV protons	Anomalous oxygen	>75 MeV protons
Periods of minimum proton flux	1.23 ± .18	1.013 ± .004	1.04 ± .25	1.041 ± .003
Periods of maximum proton flux	0.82 ± .13	1.006 ± .003	0.58 ± .17	1.047 ± .004
Expected for 15%/AU	1.05	---	1.20	---
Expected for 3 - 5%/AU	---	1.009 - 1.015	---	1.038 - 1.065
Average radial position	~ 4 AU		~ 7.2 AU	
Average radial separation	~ 0.3 AU		~ 1.25 AU	

In conclusion we have reported the observation of large recurrent temporal variations in the anomalous oxygen component. Several characteristics of these increases indicate that they are not high energy extensions of CIR events. We cannot, at this time, determine whether they are due to a peculiar short term modulation or transport mechanism or whether the particles are being accelerated locally in the interplanetary medium. In the future we will study the behavior of other particles, in particular the anomalous helium component. In addition, it may be possible to use near-Earth data, particularly in 1978, to determine the large scale radial gradient associated with oxygen increases in the region from 1 to 4 AU.

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